The Penetrating Power of the γ-Rays from Radium C.

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The primary object of the present research was to find out if there is any residual radiation from radium C after the γ-rays of ordinary penetrating power have been entirely absorbed. In the course of the work it was necessary to measure the absorption of the γ-rays by mercury. This, also, has therefore been investigated in some detail. Only experimental results are given in this paper. A discussion of the theoretical meaning of the results will be given in a subsequent paper dealing with hardening and scattering of γ-rays.

A very penetrating radiation may be looked upon either as a new type of radiation, resembling the γ-ray in that it is uncharged, but possessing a much greater penetrating power, or, if the assumption be made that the γ-rays are heterogeneous, as the most penetrating constituents of the γ-ray beam. The recent work of Danysz* has shown clearly that some of the β-rays from radium C are ejected with a velocity not less than 99 per cent. of that of light. It is not unreasonable to expect that there are γ-rays corresponding to these, and possessing, therefore, a much greater penetrating power than the average penetrating power of ordinary γ-rays. This radiation, if it exists, would be present in the γ-ray beam only in very small amount, and detectable, therefore, only when a large source of radium is used, and special precautions taken.

In a previous paper it has been shown by F. and W. M. Soddy and the author† that, when measured under conditions such that no scattered radiation of any kind enters the electroscope, the γ-rays are absorbed, apparently according to a strictly exponential law, over a range of thickness of lead of 2 to 22 cm.; or, expressed mathematically, if I_{t_1} be the intensity of the γ-rays after traversing a thickness t_1 of metal, I_{t_2} the intensity after traversing a thickness t_2, it was found experimentally that

$$I_{t_2}/I_{t_1} = e^{-\mu(t_2-t_1)},$$

where e is the base of the natural system of logarithms, and μ is a constant,

* J. Danysz, 'Compt. Rend.,' 1911, vol. 153, pp. 339, 1066; 'Le Radium,' 1912, vol. 9, p. 1.

† F. and W. M. Soddy and A. S. Russell, 'Phil. Mag.,' 1910, vol. 19, p. 725.

the absorption coefficient. μ is constant from 2 to 22 cm. of lead, and has the value 0·498 $cm.^{-1}$.

In this work, difficulty was experienced in making accurate measurements from the 18th to the 22nd cm., owing to the smallness of the ionisation from the source of radium used. For this reason, it was impossible to say with certainty, whether or not there was any radiation which penetrated the greater of these thicknesses. The result found indicated that the effect due to these rays, if it exists at all, must be very small. It was desirable therefore to repeat the work under more favourable conditions with a large quantity of radium C. To detect this very penetrating radiation, the following conditions were thought most likely to give the desired result:—

(1) A strong source of radium C to be placed as near the detecting vessel as possible. This requires the use of as dense a metal as possible as an absorbent of ordinary γ-rays.

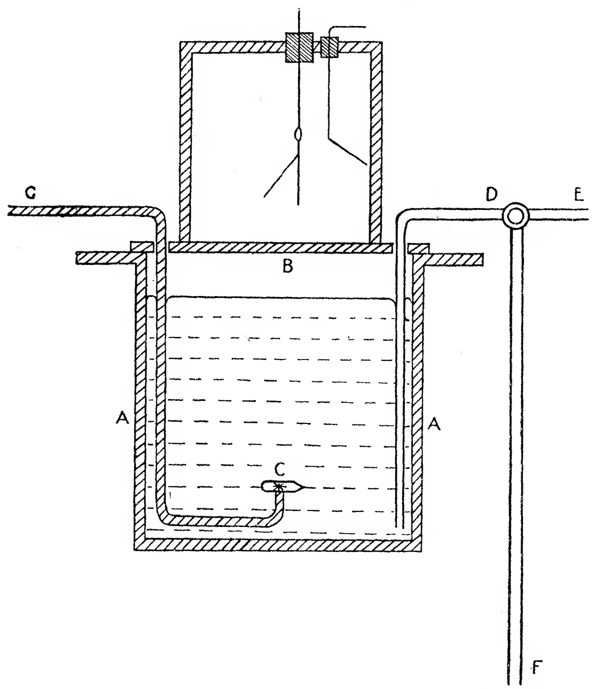
(2) Total exclusion of any scattered radiation from entering the electroscope through the sides and top.

(3) A detecting vessel which is sensitive and possesses a very low natural leak. It is essential that the ionisation chamber be large, in order that the air it contains may have a good opportunity of being ionised by the rays.

The reasons for these conditions are sufficiently obvious, and need not be discussed at length. The source used at the commencement of the experiments was about 300 millicuries of emanation. Mercury was employed as absorber of the γ-rays, as it has a greater density than any other common metal; and, therefore, a given thickness of this metal absorbs more γ-rays than the same thickness, say, of lead. The effect of scattered radiation was obviated by surrounding the source of rays on every side by at least 10 cm. of mercury. This reduced the rays moving in every direction to a very small percentage of their original intensity. Any scattered radiation, produced by the rays which escaped, was completely absorbed by the thick lead walls of the electroscope.

On p. 77 is given a diagram of the apparatus used in the chief experiment. A is a cylindrical pot of cast iron, of inside diameter 30·5 cm., and inside height 33·5 cm. When filled to the top it held 350 kgrm. of mercury. On top of this pot was laid a circular disc of lead B, 35 cm. in diameter, and 1 cm. in thickness. A large electroscope of the ordinary type was placed on the disc. The lead used for the disc and for the electroscope was the oldest procurable, in order that the latter might have as low a natural leak as possible. The electroscope had an inside diameter of 20 cm., an inside height of 21·5 cm., and a wall thickness of sides and top of 1 cm. It contained 6·75 litres of air. The leaf system consisted of a strip of brass,

7 cm. long, to which was attached a gold leaf, 6 cm. long. Insulation was effected by means of a very small bead of sulphur. Two cylinders of lead, 6 cm. long and 3 cm. inside diameter, and 1 cm. wall thickness, encircled the windows to prevent any scattered radiation from entering through them. The windows were circular and of the same diameter as the lead cylinders. The latter were just large enough to allow the reading microscope to be inserted. The microscope used had a magnification of about 9·5.



The source of radium emanation was contained in two sealed glass tubes, C, which could be attached by means of string to one end of an iron rod. The rod was connected by a clamp at G to a stand, and bent in such a way that, by raising or lowering G, the radium could be raised or lowered centrally in the mercury. By means of the glass apparatus D, which contained a three-way tap, the mercury could be added to the pot by pouring it in through E, or withdrawn by siphoning it off through F. The pot was carefully made and had a very uniform diameter. From the weight added to or withdrawn from the pot, therefore, the increase or decrease of thickness of the mercury covering the radium could be easily calculated. The natural leak of the electroscope was 0·45 division per minute, which was considered low for an instrument of these dimensions. One millicurie of emanation at a distance of 25 cm. below the lead base of the electroscope gave a leak of 36 divisions per minute.

Attempts to Detect the very Penetrating Radiation.

Two different experiments were made to detect the very penetrating radiation. The first was done at atmospheric pressure with the apparatus described above, the second was done with an ionisation chamber at high pressure. The first experiment was carried out as follows: The pot was filled to the top with mercury, and the natural leak measured three times for intervals of about 40 minutes each, with the source of radium removed entirely from the laboratory. The radium was then inserted to a depth of 20 cm. below the mercury, and the leak measured over a period of 20 minutes. The value of the leak obtained was considerably higher than the natural leak. The radium was then lowered to various depths, the leaks being carefully measured at each position, until a depth was reached at which there was no difference between the leak measured and the natural leak. The results actually obtained are given in the accompanying table:—

Table I.

Depth of radium below the mercury in cm.	Leak in division per min.
20	1·44
22	0·64
25	0·48
27	0·45
30	0·44
33	0·45

Natural leak, 0·45, 0·46, 0·44 division per min.

It is seen that at a depth of 25 cm. the ionisation due to the γ-radiation is only 7 per cent. of the natural leak of the electroscope. At greater depths this leak disappears entirely. There is, therefore, no γ-radiation capable of penetrating 27 cm. of mercury and of being detected in the electroscope used. The experiment shows also the complete absence of any secondary radiation entering the electroscope otherwise than through the base.

An ionisation chamber capable of withstanding a pressure of 80 atmospheres, was next used instead of the electroscope as a detecting vessel. The apparatus was kindly placed at my disposal by Mr. D. C. H. Florance, who employed it in a research which will soon be published. Inside the pressure chamber were mounted centrally two concentric cylinders of brass. The outer one was 22·5 cm. long and 6·3 cm. in diameter, the inner one 21·6 cm. long and 1·9 cm. in diameter. The former was charged to a

potential of 1500 volts, the latter was connected to one pair of quadrants of a sensitive Dolezalek electrometer. The pressure chamber itself was earthed.

Ionisation took place in the space between the cylinders. The pressure in the chamber was kept constant at 80 atmospheres. This arrangement is not so sensitive as the large electroscope, but it was used for two reasons. It is possible that the very penetrating rays might ionise dense gases only. Secondly, a large quantity of incident and emergent β-radiation from the very penetrating γ-rays might be produced when they strike the brass cylinders. Such radiation when produced would be an efficient ioniser of a gas at high pressure. When the radium was sunk to a depth of 26 cm. in the mercury, however, the leak of the electrometer was exactly the natural leak. No trace whatever of any radiation could be detected. I have to thank Mr. Florance for kindly making the necessary measurements for me.

The Absorption of the γ-Rays by Mercury.

The absorption of the γ-rays of radium C by mercury over a range of thickness of 1–22·5 cm. was next investigated. The radium was inserted centrally below the electroscope at a distance of 25 cm. and the pot filled with mercury. The leak was then measured. Ten kilogrammes of mercury were then siphoned off, and the leak again measured. More mercury was then siphoned off, and again the leak taken. This was continued until the leak was too large to measure. Smaller quantities of radium were then substituted for the larger quantity, and the absorption measurements continued till only 6 cm. covered the radium. At this stage a smaller lead electroscope, having a volume one-fifth of that of the larger, was substituted for it, and used for the absorption measurements from 1 to 6 cm. This was necessitated by the powerful nature of the source used. Experiments were conducted usually so that the leak was about 10 divisions per minute at the commencement, and about 1 division per minute or less at the end, of the range of thickness investigated. With the larger electroscope it was essential that the leaks should not be too great, owing to a possible lack of saturation in so great a volume of air. The results obtained are given in the table that follows: In the first column is put the range of thickness × density of mercury covering the radium. The values given are obtained directly from the weight of mercury and the dimensions of the pot. In the second column are put the values of the absorption coefficient divided by the density of mercury. All thicknesses in the tables which follow are given in centimetres, and all values of μ are μ cm.$^{-1}$.

Table II.

Range of thickness × density.		$\frac{\mu}{d} \times 100$.
14 to	72	4·39
44	102	4·34
100	140	4·36
136	225	4·39
132	307	4·39
Mean value 14 to	307	4·38

The values of μ/d were obtained as follows:—The logarithms of the ionisation were plotted against the product of thickness and density. On the average there was a point for every 12 units of thickness × density. From this straight line the mean value of μ/d over the range under investigation was obtained. Each of the five experiments was separately carried out, and is quite distinct from the other four. It is seen that the values of μ/d do not differ by more than about 2 per cent. over the entire range investigated.

Two examples showing how closely the exponential law of absorption holds are given in the two following tables. The first table deals with the first part of the range investigated, the second with the last part. In the first column of each table is given the absolute thickness × density of mercury over the radium, in the second the observed values of the ionisation, and in the third the calculated values. For convenience, the observed value of the ionisation for the smallest thickness × density is in both tables put at 1000. The theoretical values are obtained from the usual equation,

$$I_{t_2}/I_{t_1} = e^{-\frac{\mu}{d}(t_2 d - t_1 d)}.$$

Table III.—Range of Thickness × Density, 13·6 to 71·6.

$\mu/d = 4·39 \times 10^{-2}$.

Thickness × density.	Observed ionisation.	Calculated ionisation.
13·6	1000	1000
21·6	700·4	697·9
30·3	479·7	472·9
38·5	330·9	335·5
46·9	229·5	232·1
55·1	160·8	162·0
63·4	111·9	112·6
71·6	78·4	78·5

Table IV.—Range of Thickness × Density, 131·9 to 307.

$\mu/d = 4{\cdot}39 \times 10^{-2}$.

Thickness × density.	Observed ionisation.	Calculated ionisation.
131 ·9	1000	994 ·2
143 ·2	607 ·4	605 ·6
156 ·7	330 ·0	335 ·1
170 ·0	187 ·4	186 ·9
183 ·7	101 ·6	102 ·4
196 ·7	57 ·79	57 ·95
208 ·7	34 ·24	34 ·24
219 ·6	20 ·51	21 ·24
234 ·2	11 ·41	11 ·19
243 ·7	7 ·48	7 ·38
256 ·6	3 ·97	4 ·19
272 ·5	2 ·05	2 ·09
307 ·0	0 ·47	0 ·46
323 ·0	<0 ·1	0 ·23

Since $\mu/d = 4{\cdot}38 \times 10^{-2}$ for mercury, and d is 13·59, $\mu = 0{\cdot}595$ cm.$^{-1}$. A thickness × density of 15·8, or a thickness of 1·164 cm. mercury, therefore, cuts the γ-rays of radium down to half value. Over the range 13·6 to 307 of thickness × density, the γ-radiation is reduced in the ratio of 360,000 to 1.

Under the conditions of experiment, the leak due to the γ-rays from 300 millicuries of emanation in the electroscope was 3·77 divisions per minute through a thickness × density of 183, and of 0·017 division per minute through 307. The radiation from 300 millicuries, if unabsorbed by mercury, would produce 10,800 divisions per minute in the electroscope. The radiation, capable of penetrating thicknesses greater than 22·5 cm. of mercury, is therefore less than 0·017÷10800, *i.e.* is less than $1{\cdot}6 \times 10^{-6}$ of the initial γ-ray beam.

The value of μ for mercury, 0·595 cm.$^{-1}$, is 7 per cent. less than a value given in a previous paper by Soddy and Russell.* In the former research the source of radium used was less than half a milligramme, and the absorption over the first 3 cm. only could be investigated.

The mean value of μ/d for mercury, $4{\cdot}38 \times 10^{-2}$ cm.$^{-1}$, is very similar to the mean value obtained in a previous research for a range of 2 to 22 cm. of lead, namely $4{\cdot}37 \times 10^{-2}$ cm.$^{-1}$. The results of this paper, both with regard to the absence of a very penetrating radiation, and to the absorption of the rays by an element of high atomic weight, confirm and extend the results previously obtained with lead as an absorbent. Beyond a thickness of 22·5 cm. of mercury it will be difficult to detect γ-rays even if large quantities of

* F. Soddy and A. S. Russell, 'Phil. Mag.,' 1909, vol. 18, p. 644.

radium are forthcoming. In the electroscope used in these experiments, the leak due to the γ-rays from 10 grm. of radium would be only 4 per cent. of the natural leak, after they had penetrated 28·5 cm. of mercury.

Summary.

(1) The γ-rays of radium C are absorbed by mercury over a range of thickness of 1 to 22·5 cm. strictly according to an exponential law. The mean value of μ/d is $4{\cdot}38 \times 10^{-2}$. Over this range the intensity is diminished in the ratio of 360,000 to 1.

(2) No trace of any radiation more penetrating than γ-rays could be detected. If any exists, and is capable of ionising air, its intensity is less than 2×10^{-6} of that of the initial γ-ray beam.

I have to express my warmest thanks to the Castner-Kellner Alkali Company of Runcorn for loaning me 800 lbs. of pure mercury, and for making for me the cast iron pot which contained it. But for their generosity in this matter, the present research could not have been carried out.

I have also to express my thanks to Prof. Rutherford, in whose laboratory this work was carried out, for his suggestions and advice.